Dark sectors in η,η' decays

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LOI with Corrado Gatto and Bastian Kubis
Other collaborators welcome

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New η and η' factories on the horizon

Upcoming experiments

Jefferson Eta Factory (JEF) at Jefferson Lab – Hall D (approved)

	η	η'	
Tagged mesons	6.5×10^7	4.9×10^7	per 100 days

Rare Eta Decays with a TPC for Optical Photons (REDTOP) possibly at Fermilab (proposed)

Phase I (untagged mode)	2×10^{13}	10^{11}	per year
Phase II+ (tagged mode)	1×10^{13}	10^{11}	

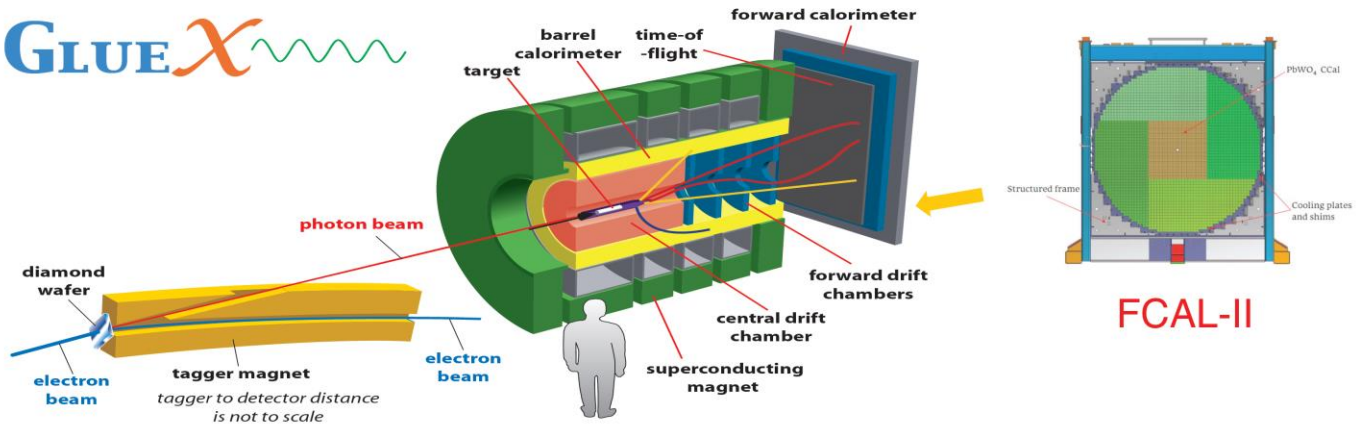
Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	~3×10^7 (p+d), ~5×10^8 (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	~10^7	~5×10^7

Jefferson Eta Factory (JEF) experiment

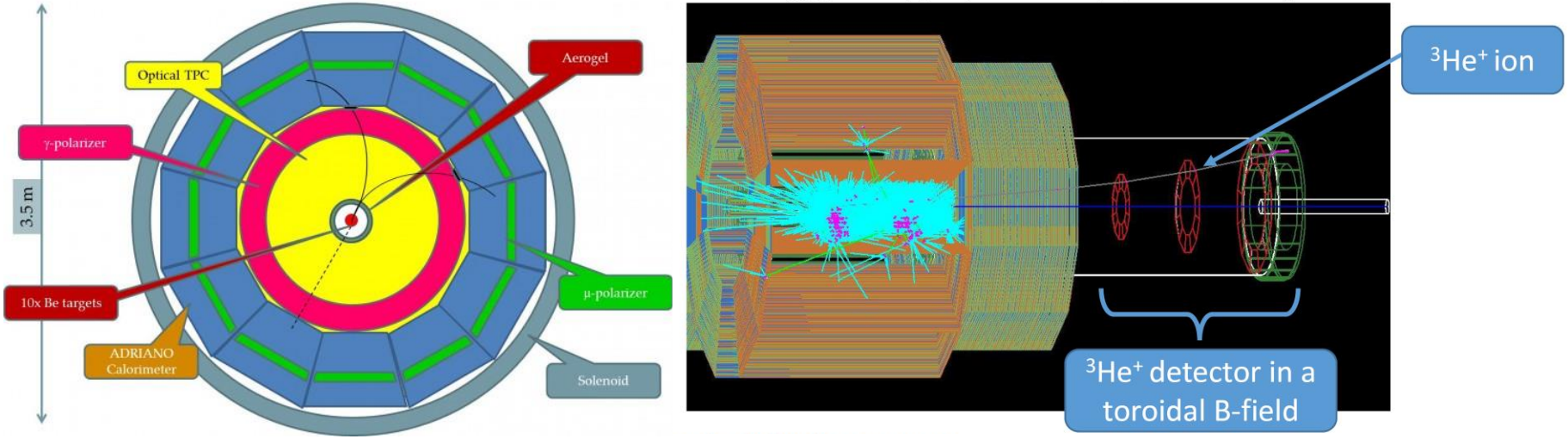
γ beam (10 GeV) on H target

GlueX + upgraded forward calorimeter at Jefferson Lab (Hall D)



Rare Eta Decays with a TPC for Optical Photons (REDTOP)

proton beam (1-3 GeV) on nuclear target (Be/D)



See talks by Liping Gan and Anna Mazzacane (RF2 session)

Rich physics program at η,η' factories

Standard Model highlights

- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests

- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)

- Vector bosons
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, ST [arxiv:2007.00664]

η, η' laboratory for dark sectors

- On-shell decays to new light particles in the MeV—GeV range
  - Vector bosons (hidden photons), scalar bosons, axion-like particles (ALPs)

- Leading decays of η are already suppressed $\sim \mathcal{O}\left(\alpha_{\rm em}^2\right)$ or $\mathcal{O}\left((m_u - m_d)^2\right)$
- Larger mass reach for η' but worse sensitivity (total width larger by ~100)

- Decays to light hidden particles are 2- or 3-body decays that mimic 3-, 4-, or 5-body final states (often very rare)

- Search strategies (visible final states):
  - Resonance searches (bump hunting)
  - Displaced vertices (long-lived decays)
  - Rare decays – new physics process mimics highly-suppressed SM channels

- Other possibilities: invisible or partially-invisible decays

Goals for Snowmass process

- Dark sector predictions and experimental sensitivities for η, η' decays
  - Including more general frameworks beyond those considered in literature
  - Since NLO corrections can be important, go beyond leading order in χPT
  - Connection with landscape of constraints and anomalies [$(g\text{-}2)_\mu$, ^{8}Be, etc.]

- Collaboration between dark sector phenomenology, χPT theory, and experiment

Dark sector models

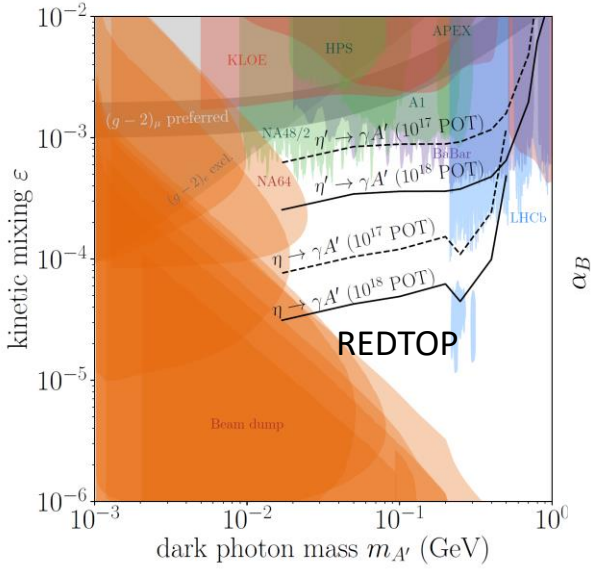
Models Theory landscape Predictions Sensitivities

Dark sector models

Models	Theory landscape	Predictions	Sensitivities
Vector bosons	✓	✓	✓

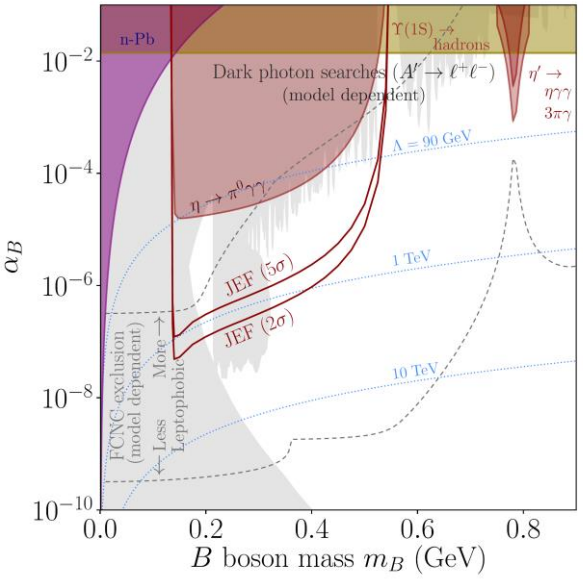
Dark photon

$$\eta, \eta' \to \gamma A' \to \gamma \ell^+ \ell^-$$



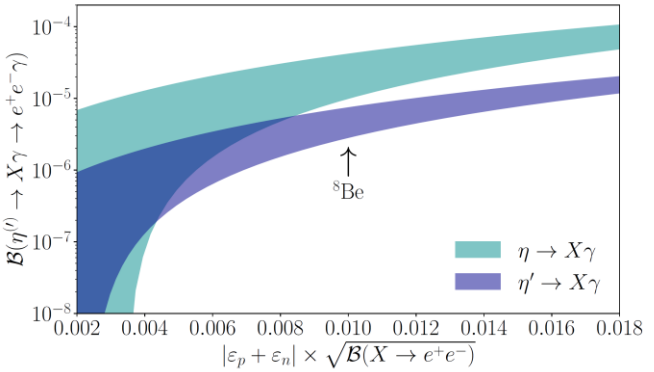
Leptophobic $U(1)_B$ boson

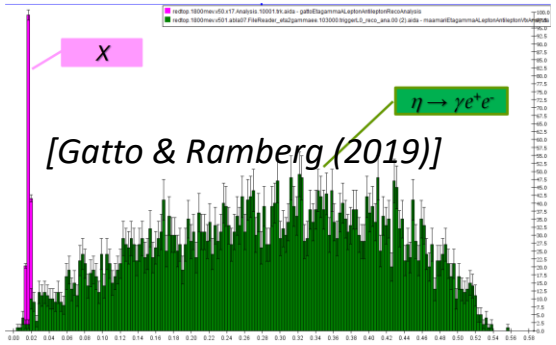
$$\eta \to B\gamma \to \pi^0 \gamma\gamma$$



[Gan et al (2020)]

Protophobic X(17) boson





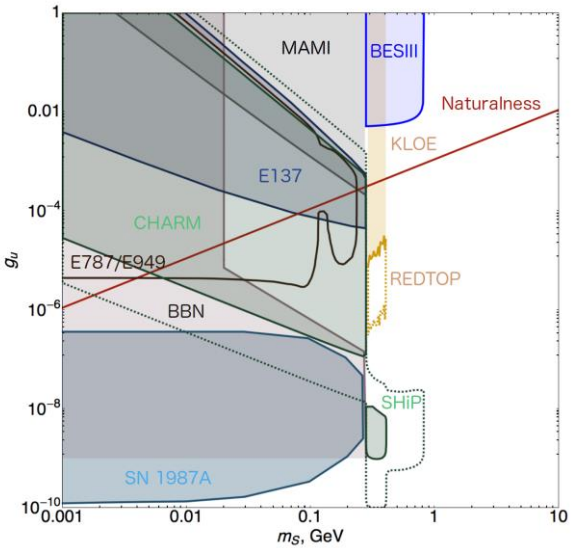
[Gatto & Ramberg (2019)]

Dark sector models

Models	Theory landscape	Predictions	Sensitivities
Vector bosons	✓	✓	✓

Scalar bosons

u-quark scalar coupling only



[Batell et al (2018)]

General signatures

$$\eta, \eta' \to \pi^0 S \to \pi^0 \ell^+ \ell^-, \quad \eta' \to \eta S \to \eta \ell^+ \ell^-$$

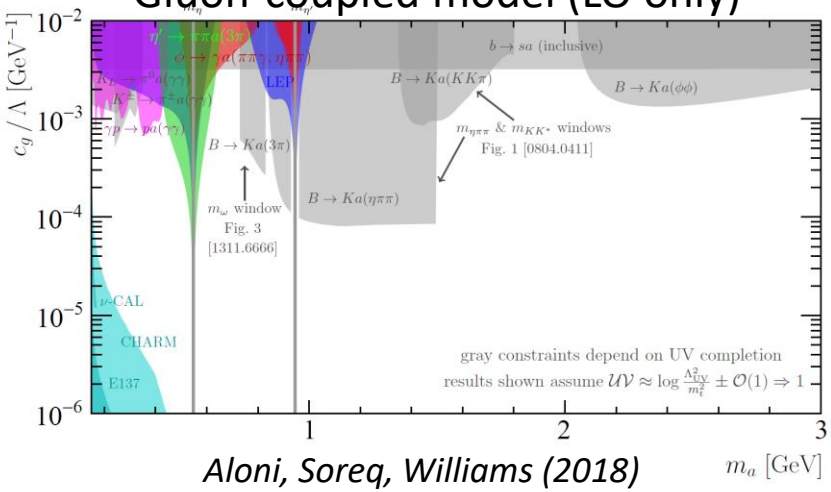
$$\eta \to \pi^0 S \to \pi^0 \gamma\gamma$$

$$\eta, \eta' \to \pi^0 S \to 3\pi, \quad \eta' \to \eta S \to \eta\pi\pi$$

Dark sector models

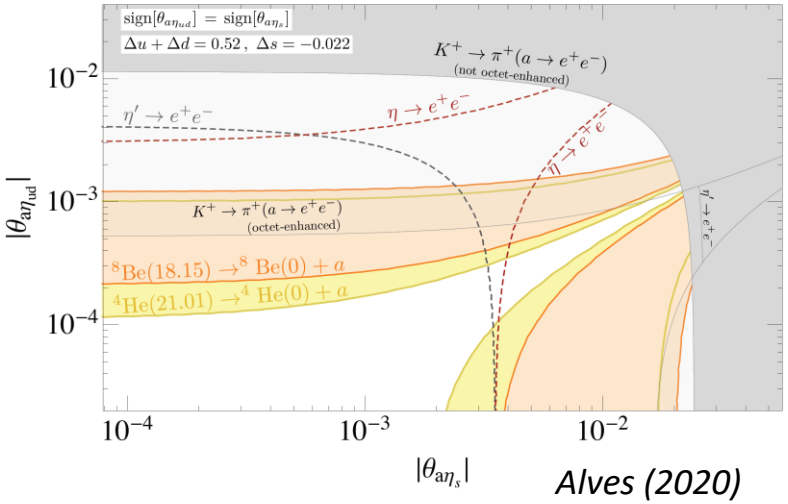
Models	Theory landscape	Predictions	Sensitivities
Vector bosons	✓	✓	✓
Scalar bosons	Go beyond simplified u-quark coupled model Study scalar form factors (esp. for η')		
Axion-like particles	η, η' constraints for simplified models only		

Gluon-coupled model (LO only)



Aloni, Soreq, Williams (2018)

Piophobic axion model (NLO)



Alves (2020)

Dark sector models

Models	Theory landscape	Predictions	Sensitivities
Vector bosons	✓	✓	✓
Scalar bosons	Go beyond simplified u-quark coupled model Study scalar form factors (esp. for η')		
Axion-like particles	Go beyond simplified models and LO predictions		

$$\eta \to \pi\pi a \to \pi\pi\gamma\gamma\,,\ \pi\pi e^+e^-\,,\ \pi\pi\mu^+\mu^-$$ (and same for η')

$$\eta' \to \pi\pi a \to \pi\pi\,\pi^+\pi^-\gamma\,,\ 5\pi$$

$$\eta' \to \eta\pi^0 a \to \eta\pi^0\gamma\gamma\,,\ \eta\pi^0 e^+e^-\,,\ \eta\pi^0\mu^+\mu^-$$

Summary

What is the motivation?

- η,η' decays offer complementary probes of dark sectors
- Synergy with Standard Model η,η' decay studies

What joint efforts are needed?

- Collaboration between theorists to explore model landscape and predictions
- Collaboration with experimentalists to study sensitivities

What is the schedule?

- To be determined

If you are interested to join this effort, let me know!